DEVELOPMENT AND APPLICATIONS OF PULSED POWER DEVICES AT THE UNIVERSITY OF TEXAS AT DALLAS*

F. Davanloo† and C. B. Collins
Center for Quantum Electronics, University of Texas at Dallas
P.O. Box 830688, Richardson, TX 75083-0688

F. J. Agee
Air Force Office of Scientific Research, AFOSR/NE
801 N. Randolph St., Arlington, VA 22203-1977

Abstract

The generic concept for the pulsers developed at the University of Texas at Dallas (UTD) employs a Blumlein based pulse forming system commutated by a fast switching device. Characterization studies of these pulsers have been extensively performed at UTD and results indicate that they are capable of producing high power waveforms with risetimes and repetition rates in the range of 0.2 - 50 ns and 1 - 1000 Hz, respectively, using a conventional thyratron, spark gap, or photoconductive switch. This report presents the progress in the development and use of these Blumlein power sources. Currently, we are exploring the impedance parameter space in our modulator pulse forming lines to develop a reliable low impedance pulser capable of generating intense ultra-fast electric fields and or x-ray pulses with nanosecond durations suitable for applications in the fields of Bioelectricity and Induced Gamma Emission.

I. INTRODUCTION

In recent years new fields of Bioelectric and Induced Gamma Emission have opened challenging applications for pulsed power research and development. Intracellular electromanipulation involves bioelectric processes that require the development of reliable pulsed power sources that produce ultra-fast electric fields larger than 50 kV/cm at pulse durations into nanosecond range [1]. Such devices are also needed to generate pulses of x-ray of short durations for irradiation of isomeric targets for study of induced gamma reactions [2].

Characterization studies of the Blumlein pulsers developed at UTD have been extensively performed. These pulsers have been used to drive x-ray diode loads with different characteristics and discharge geometries. High dose rates of x-rays with pulse duration in the range 3-20 ns have been obtained. Recently, the pulser design has been adapted to enable it to reliably produce powers as great as 80 MW, in nanosecond pulses with risetimes on the order of 200 ps. These devices have compact line geometries and are commutated by an avalanche GaAs photoconductive semiconductor switch (PCSS) triggered with a low power laser diode array. Significant lifetime improvements for PCSS have been achieved by advanced switch treatments with amorphic diamond coatings also developed at UTD [3].

The principal objective of our current research is to enlarge the pulser technology base, level of understanding and design options that make optimal use of the PCSS capabilities for generation of high repetition ultra-fast pulses. In this work we present the progress in the development and use of these novel Blumlein pulsers toward generating intense ultra-fast voltage and x-ray pulses with nanosecond durations for applications in the fields of Bioelectricity and Induced Gamma Emission.

II. ISOMER RESEARCH APPLICATIONS

One of the new research directions currently opening involves the modulation of nuclear properties. Of particular interest are nuclear spin isomers. They store the highest densities of energy possible without nuclear reactions. For example, an isomer of ^{178}Hf stores 2.445 MeV per atom for a shelf life of 31 years. In practical terms this means that a sample of the size of a golf ball would store the energy equal to 10 tons of chemical fuels or explosives. However, in nuclear spin isomers the energy is stored electromagnetically so that it would be released as x-rays and γ-rays, if it could be triggered. Since isomers derive their long shelf lives from their poor coupling to electromagnetic waves, it was traditionally thought to be impossible to trigger the release of the stored energy. A recent and major breakthrough [2] in Isomer research has demonstrated a way of excitation to couple energy into ^{178}Hf^{m2} isomeric nuclei causing excitation from the long-lived isomeric state to a state with a much shorter lifetime.

* Work supported by the Air Force Office of Scientific Research (AFOSR) under Grant F49620-00-1-0296.
† email: fdavan@utdallas.edu.

0-7803-7915-2/03/$17.00 ©2003IEEE.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 2003	**N/A**	**-**

4. TITLE AND SUBTITLE
Development And Applications Of Pulsed Power Devices At The University Of Texas At Dallas

5a. CONTRACT NUMBER
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER
5e. TASK NUMBER
5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Center for Quantum Electronics, University of Texas at Dallas P.O. Box 830688, Richardson, TX 75083-0688

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR’S ACRONYM(S)

11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. IEEE International Pulsed Power Conference (19th). Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

14. ABSTRACT
The generic concept for the pulsers developed at the University of Texas at Dallas (UTD) employs a Blumlein based pulse forming system commutated by a fast switching device. Characterization studies of these pulsers have been extensively performed at UTD and results indicate that they are capable of producing high power waveforms with risetimes and repetition rates in the range of 0.2 - 50 ns and 1 - 1000 Hz, respectively, using a conventional thyratron, spark gap, or photoconductive switch. This report presents the progress in the development and use of these Blumlein power sources. Currently, we are exploring the impedance parameter space in our modulator pulse forming lines to develop a reliable low impedance pulser capable of generating intense ultra-fast electric fields and or x-ray pulses with nanosecond durations suitable for applications in the fields of Bioelectricity and Induced Gamma Emission.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**4**	

Important to the success of the Isomer Research is the in-house accessibility of a source of pulses of x-ray of short duration that is very powerful in comparison with conventional devices. In recent isomer experiments, the isomeric targets were irradiated with x-rays photons at the SPring-8 synchrotron radiation facility with energies tuned from 9-13 keV [2]. Synchrotrons such as Spring-8 have the advantages of collimation and tunability. However, these devices are few in number and require complex supporting facilities resulting in experimental time being at a premium.

A. Flash X-ray Devices

For the past several years our group at UTD has been involved in development and characterization of compact Blumlein based flash x-ray generators. High dose rates of x-rays with pulse duration in the range 3-20 ns have been obtained using a thyratron or a spark gap as the switching device. Our recent efforts have for the first time resulted in implementation and demonstration of several high-power stacked Blumlein pulsers commutated by a single photoconductive switch. Prospects for producing x-rays with such fast-switching devices are very interesting and discussed in this report.

1) Pulser design and construction review

Design and construction of the pulse forming system for these Blumlein generators were given elsewhere [4]. Briefly, a single Blumlein pulse generator consisted of two critical subassemblies: (1) a single Blumlein pulse forming line, and (2) a commutation system capable of operation at high repetition rates. The basic organization is shown schematically in Fig. 1 (a). The Blumleins were constructed from copper plates, potted with epoxy on outer surfaces to reduce corona, and separated by laminated layered Kapton (polyimide) dielectrics. Scaling of these devices was studied by construction of several separate systems with different lengths, capacitances, and impedances [5]. All Blumleins had a smooth taper that increased from the load diode end to the switching end as seen in Fig. 1 (a).

To access voltages far above 100 kV, a stacked Blumlein pulse generator was designed and constructed [4,6]. It consisted of three separate but integrated subassemblies: (1) the switching assembly, (2) pulse forming Blumleins, and (3) the pulse stacking module. The basic organization for the second prototype stack Blumlein pulse generator with twelve Blumlein lines is shown in Fig. 1 (b). In operation, both the single and stacked Blumlein pulse generators were resonantly pulse charged in the range of 3-75 kV and repetition rates of 1-1000 Hz. Voltage and current amplitudes in the range of 10-600 kV and 0.1-20 kA, respectfully have been produced with these devices.

2) Flash X-ray Production and Characteristics

Blumlein Pulse Power sources developed at UTD have been mainly used to drive x-ray diode loads. Several x-ray diodes have been constructed with a variety of materials and discharge geometries. Reasonable matching of these heads to the pulse generators has allowed production of high power x-ray pulses with durations as short as 3 ns. Two basic diode configurations for low-voltage and high-voltage operations have been used.

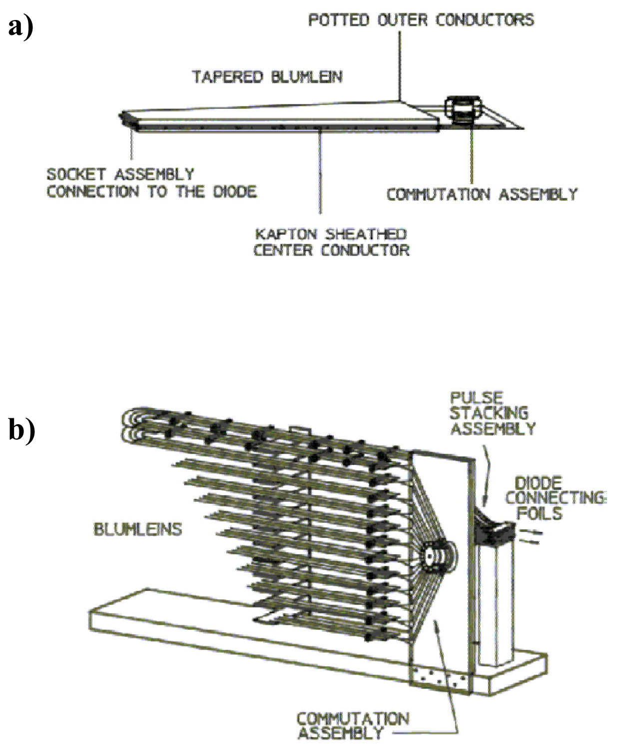

Figure 1. (a) Schematic drawing of pulse generator with a single traxial Blumlein. (b) Schematic drawing of pulse generator with several Blumlein modules connected in parallel at switching end and stacked in series across the load diode.

Characterizations of the flash x-ray systems driven by Blumlein pulser have been given in detail elsewhere [5,6]. Compact flash x-ray sources producing dose rates exceeding 1 kR min^{-1} have been realized utilizing single Blumlein pulsers as the power source. Interchangeability of discharge anodes has provided for a significant fraction of the output to be extracted in the K lines of Cu, Mo, Nb, and Ag. In less than 1 min of experimental time, a peak spectral density is radiated from these devices that exceeds 1 x 10^{18} keV/keV.

Methods of x-ray spectroscopy inapplicable to single shot systems have been used to record the spectral contents of the outputs. A low-voltage configuration was used in the x-ray diodes matched to the single line pulse generators. With this type of diode geometry, about one-third of the pulse energy appeared in the lines of the anode materials. The remainder was distributed over a fairly broad band of true continua. Substantial radiation from photons with energies up to 450 keV were emitted from the high-voltage diode matched to a stacked Blumlein pulser. Output was a true continuum, peaking in intensities of 5 x 10^{8} photons/keV/shot and containing useful intensities of photons having energies of 450 keV.

In this case, peak x-ray powers exceeded 10^7 R/sec at the output window of the device.

The temporal evolution of the x-ray output from the high voltage diode is shown in Fig. 2, together with the time dependence of the open circuit and discharge voltages and the current at the diode. Because of the higher discharge voltages realized in the transmission geometry of the diode, bremsstrahlung production was peaked in the forward direction.

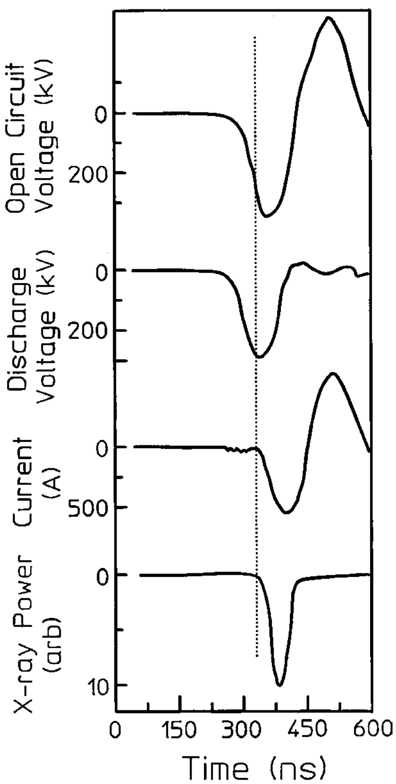

Figure 2. Typical relationship between the voltages, current, and x-ray output emitted from a high-voltage diode powered by the stacked Blumlein pulser. The dotted line demonstrates the synchronization of the current and x-ray pulse with the moment when the discharge and open circuit voltages begin to differ.

3) Prospect for X-rays with 100 ps Switching

Our recent efforts have resulted in implementation and demonstration of several intense photoconductively switched stacked Blumlein pulsers. Presently, these devices operate with a switch peak power in the range of 50-80 MW and activating laser pulse energies as low as 300 nJ [3,4]. Examinations of output waveforms have indicated pulse durations in the range of 1-5 ns and risetimes as fast as 150 ps. An example of the output voltage generated by a 2-line stacked prototype with Blumlein impedance of about 100 Ω and Blumlein length of 11 cm is given in Fig. 3. Pulse durations of voltage and current waveforms generated were proportional to the Blumlein length corresponding approximately to the two way transit time of Blumleins. Peak voltage value for pulse presented in Fig. 3 was 98 kV and corresponded to a voltage gain of 1.96. Since the stacked Blumlein impedance was closely matched to a non-inductive resistive load, the output current pulse shape, duration and rise time was similar to voltage pulse shown in Fig. 3. Peak current value for the conditions shown in Fig. 3 was about 0.5 kA consistent with the voltage gain and resistive load matching.

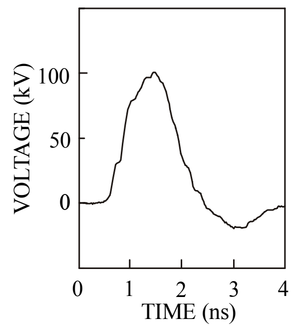

Figure 3. Output voltage waveform generated by a two-line stacked Blumlein prototype pulser commutated with a photoconductive switch.

In all the Blumlein based flash x-ray systems we have developed, the commutation of pulsers has been affected by a thyratron or a spark gap and the x-ray production was source limited. Furthermore, in all cases under optimized charging voltage and diode gap settings where the impedance of diode matched to the Blumlein pulser, the temporal evolution of pulses followed closely those shown in Fig. 2. At lower diode gap settings and under the best match conditions, the diode current pulse oscillation was reduced. It should be noted that open circuit voltage pulse rise time shown in Fig. 2 corresponds to the switching time of commutation device which in this case was a thyratron.

It is interesting to explore the use of photconductively-switched Blumlein devices described in earlier to produce flash x-rays. The principal challenge is the development of a low geometric profile x-ray diode that could be matched to the Blumlein pulser commutated with a photoconductive switch. Since the resistive load and open circuit voltages have rise times on the order of 200 ps, it is expected that the diode closure would be dominated by the electric characteristics of the pulser and discharge would be source limited. In this case the temporal evolution of diode x-ray output and the time dependence of the open circuit, discharge voltage and the current at the diode should resemble those shown in Fig. 2.

As seen in this figure, a rapid rise of current should start at the time where the discharge voltage begins to break from the open circuit ringing. The x-ray output production is then expected to start with the rapid growth of current and should drop off as discharge voltage falls and ceases. Since the pulse rise time available from the photoconductively-switched pulser is on the order of 200 ps, the generated x-ray pulse rise time is expected to be less than 100 ps. X-ray pulse duration depends on the discharge voltage pulse width that in this case should be on the order of 1-2 ns.

Flash x-ray systems powered by Blumlein pulse generators have been used to excite the fluorescence from high-pressure rare gas plasmas. The deposition of hundreds of millirads of x-rays in nanosecond pulses into tens of atmospheres of argon gases has resulted in a strong excitation of the VUV spectra that depends upon the generation of highly ionized precursors. Our current application concerns the use of these flash x-ray devices to excite nuclear transitions where the ultimate signal to noise ratio will depend only upon the total radiation that can be delivered to an extended absorber in a working period. Production of such ultra-fast flash x-rays discussed in this report should facilitate our studies. It is reasonable to expect that some other applications as well may find benefit in such laboratory scale flash x-ray device.

III. BIOELECTRICS APPLICATIONS

During last couple of years new areas of pulsed power application have been introduced for the field of Bioelectrics [7]. These include biofouling prevention, bacterial decontamination, and medical applications such as electrochemotherapy and gene therapy. These applications are usually classified as outer membrane bioelectric effects. Very recently, a major discovery was reported by Schoenbach, et al [1] where initial approaches to apply pulsed electric fields to kill cells by apoptosis were investigated. There, it was demonstrated as the applied pulse duration decreases from 300 ns to 10 ns, electric field effects are reduced at the level of the plasma membrane and are focused to the cell interior. If the electric field intensity is high enough apoptosis can be induced as indicated by the reduced size of treated mouse tumors [1]. This type of field-cell interaction using nanosecond pulses with high electric field has potential to affect transport processes across sub-cellular membranes and may be used for gene transfer into cell nuclei [1]. It can also trigger intracellular processes that can be used for cancer treatment by programmed cell death.

The intracellular electromanipulation processes require the development of reliable pulsed power sources that produce electric fields larger than 50 kV/cm at pulse durations into nanosecond range [1]. In addition, the relatively low impedance of biological loads requires the characteristic impedance of the pulse generator to be around 10 Ω. Blumlein pulse generators are most suitable for the intracellular electromanipulations applications in the Bioelectric field because they have low inductance geometry that permits generation of ultra fast waveforms easily matched and delivered to the biological loads.

It should be noted that the utilization of pulse power technology to treat cancer in human subjects requires non-intrusive methods such as ultra-wideband (UWB) transmitters. Such devices could be used to provide necessary electric field strengths and durations at a tumor location in human body to promote apoptosis and cancer treatment. Sources employing UWB schemes feature fast rising short pulse width waveforms with broad frequency content that are suitable for intracellular electromanipulations.

The development of UWB sources has been pursued in two general directions. The first uses a single pulser to feed a very high voltage to a single antenna transmitter. The pulser can be used to feed a non-dispersive high gain antenna system to achieve high field strength in the far field of the antenna. The second approach employs many radiating elements (array UWB source) switched at relatively low voltage to collectively deliver an additive field at the target of the array. The photoconductive semiconductor switched (PCSS) array method has been employed and demonstrated in the systems such as GEM series of pulsers at the U.S. Air Force Research Laboratory [8]. Such UWB schemes can provide non-intrusive probe of human body for medical treatments if suitable electric strength and pulse parameters are identified.

Presently, we are exploring the impedance parameter space in our modulator pulse forming lines to develop a reliable low impedance pulser capable of generating intense ultra-fast waveforms with nanosecond durations for applications in the field of Bioelectric.

IV. REFERENCES

[1] K. H. Schoenbach, S. Katsuki, R. H. Stark, E. S. Buescher and S. J. Beebe, “Bioelectrics-New applications for pulsed power technology,” IEEE Trans. Plasma Sciences **30**, pp. 293-301, 2002.

[2] C. B. Collins, N. C. Zoita, A. C. Rusu, M. C. Iosif, F. Davanloo, S. Emura, T. Uruga, R. Dussart, J. M. Pouvesle, C. A. Ur, I. I. Popescu, V. I. Kirischuk, N. V. Strilchuk, and F. J. Agee, “Tunable synchrotron radiation used to induce gamma-emission from the 31 year isomer of ^{178}Hf,” Europhys. Lett., **57**, pp. 677-682, 2002.

[3] F. Davanloo, C.B. Collins, and F.J. Agee, “High-Power Photoconductive Semiconductor Switches Treated with Amorphic Diamond Coatings,” IEEE Trans. Plasma Sciences, **30**, pp. 1897-1904, 2002.

[4] F. Davanloo, C.B. Collins, and F.J. Agee, “High Power, Repetitive-Stacked Blumlein Pulsers Commutated by a Single Switching Element,” IEEE Trans. Plasma Sciences, Vol. 26, pp. 1463-1475, Oct. 1998.

[5] F. Davanloo, C.B. Collins, and F.J. Agee, “Flash X-ray Sources Powered by Blumlein Pulsers – Review and Prospect for X-rays with 100 ps Switching,” Proc. SPIE 4786, pp. 162-172, 2002.

[6] J. J. Coogan, F. Davanloo, and C. B. Collins, “Production of High Energy Photons from Flash X-ray Sources Powered by Stacked Blumlein Generators,” Rev. Sci. lnstrum. **59**, pp. 2260-2264, 1988.

[7] C. Polk, “Biological applications of large electric fields: Some history and fundamentals, IEEE Trans. Plasma Sciences **28**, pp. 6-14, 2000.

[8] F. J. Agee, D. W. Scholfield, W. Prather and J. W. Burger, “Powerful Ultra-Wide Band Emitters: Status and Challenges,” Proc. SPIE 2557, pp. 98-106, 1995.